Transforming agricultural land use through marginal gains in the food system

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Abstract

There is an increasing need for transformational changes in the global food system to deliver healthy nutritional outcomes for a growing population while simultaneously ensuring environmental sustainability. However, such changes are subject to political and public constraints that usually allow only gradual, incremental changes to occur. Drawing inspiration from the British cycling team's concept of marginal gains, we show how transformation might be reconciled with incremental changes. We demonstrate that a set of marginal food system changes acting to increase production efficiency, to reduce losses or to adjust diets could collectively reduce the agricultural land required globally for food production by 21%, or over a third given higher adoption rates. The results show that while all categories of action are important, changes in consumer choices in Europe, North America and Oceania and in the supply-chain in Africa and West and Central Asia have the greatest potential to reduce the land footprint of the food system.

1 The need to transform the global food system

Agriculture uses 38% of all land (FAOSTAT, 2018a) and provides the global population with food, fuel and fibre. In the wake of rapid population growth (UN, 2017), increasing consumption per capita, and increasing demand for livestock products in countries with growing economies (Alexander et al., 2015; Delgado, 2003; Godfray et al., 2018), total food demand is projected to rise by 52 – 116% by 2100 from 2005 levels (Popp et al., 2017). This, in turn, is predicted to drive further agricultural expansion into natural ecosystems (Alexander et al., 2018; Alexandratos and Bruinsma, 2012; Bowles et al., 2019; Butler and Laurance, 2009). Agricultural expansion, combined with the intensive use of agricultural inputs, underlies increasing rates of species extinction (Alroy, 2017; Grooten and Almond, 2018), the degradation of biodiversity and ecosystem services (Haines-Young and Potschin, 2010; West et al., 2010) and agricultural greenhouse gas emissions that contribute to climate change (Smith et al., 2014). Mitigating these impacts is likely to require a substantial reduction in the land footprint of agriculture, necessitating a process of transformation in the food system (Foresight, 2011).

The concept of 'transformation' is widely discussed with respect to climate change adaptation (Kates et al., 2012; Rickards and Howden, 2012), with calls for "major, non-marginal change[s]" (Stern et al., 2006). However, the concept of transformation is increasingly criticised for its failure to direct policy change at an achievable and sustainable scale and does not take account of the complexity and inertia in human systems (Brown et al., 2019; Görg et al., 2017; Vermeulen et al., 2018; Willett et al., 2019). Instead, policy-makers tend to favour the pursuit of incremental change (Dunn et al., 2017; Mapfumo et al., 2017). Drawing inspiration from an unlikely source - the British cycling team and their search for success through the concept of marginal gains - we aim to show how the concept of transformation might be reconciled with incremental change and how this may prove a valuable tool in the transformation of the global food system.

Sir Dave Brailsford oversaw the rise of British cycling to a position of pre-eminence in international competitions: Britain has won 50% of all track and road cycling gold medals during the last two Olympic Games, and six of the last seven winners of the Tour de France were British riders competing for the Brailsford-led British team (Team Sky). Brailsford attributed this success to the concept of marginal gains (BBC News, 2015). Marginal gains describes how significant overall improvements might be achieved through the effects of making multiple small changes across the system as a whole. When each small change acts in isolation, its effect on performance are negligible. However, acting in combination, marginal gains produce a much larger improvement in performance. The competitive results of British cycling could certainly be described as transformational. So, could the marginal gains effect be beneficial elsewhere? The concept has already been applied beyond the realm of sports, for example in the transformation of healthcare and aviation (Syed, 2015). We hypothesise that marginal gains could also be applied successfully to the global food system.

We apply the concept of multiple marginal gains to estimate achievable reductions in agricultural land areas. We believe that this is a way of sidestepping the potentially futile search for a 'silver bullet', or step-change, to transform the food system. Individual step-change transformations are unlikely as there are limited opportunities for the widespread implementation of these types of improvements. For example, factors to increase production efficiency, such as improved crop breeding and genetic techniques, are hampered by a lack of investment in research and development and face barriers to adoption from policy, intellectual property ownership, and time lags in acceptance (Brown et al., 2019). Instead, we explore a suite of achievable marginal changes in the food system that could collectively result in transformation. To explore this hypothesis, we first identify changes and then model their combined effect on the land area required for global food production.

2 Marginal food system changes

We selected 29 diverse, marginal changes (Table 1) each with the potential to reduce agricultural land area, based on existing literature (as detailed below). The changes fall into three interlinked categories—increasing production efficiency, reducing losses, and shifting diets—widely targeted for their potential to create a more sustainable food system (Foley et al., 2005; Godfray et al., 2010; Springmann et al., 2018). Rather than adhere to Brailsford's original 1% gains, we considered the plausibility of each gain in turn, and used the analysis to explore (rather than predict) the overall effect of the marginal gains approach. The rate of each change was chosen to represent the improvement that can be achieved over a short to medium time horizon (5-15 years). However, given the exploratory nature of the analysis these outcomes are not intended to be projections of a specific year, and do not account for other changes, e.g., in populations, incomes or climate. The changes outlined were considered marginal under the assumption that they act on the food system at rates selected from between 0.5 – 5%, with only the changes relating to reductions in sources of losses or waste assigned a rate of greater than 3%. The context used to select these rates is given below, and briefly summarised in Table 1. In principle, these low rates of change should be more achievable than greater changes in a smaller number of factors, i.e. the step-change approach to transformation.

Table 1: Summary of changes to the food system considered with the potential for marginal gains in food system efficiency, and the overall rates of assumed action. Orange shading indicates consumer or retailer behavioural changes, while blue shading indicates supply changes to production or value-chains.

	Change	Justification summary	Rate	Action
Production efficiency	1: Crop management practices	Improvements in planting, harvesting and other actions. Better pest/disease control.	2%	Increase in crop yields.
	2: Crop breeding	Continued development of improved varieties using conventional breeding techniques.	1%	
	3: Crop genetic modification	Crop improvements through genetic modification or editing. Issues with regulatory and public acceptance.	2%	
	4: Pasture management	Better pasture management and intensification of grassland production.	2%	Increase in pasture yields.
	5: Livestock husbandry practices	Education and knowledge exchange, to disseminate best practice globally.	2%	Increase in feed conversion ratios.
	6: Livestock breeding	Continued development of improved livestock genetics and selection using conventional techniques.	1%	
	7: Livestock genetic modification	Livestock improvements through genetic modification or editing. Issues with regulatory and public acceptance.	2%	
	8: International trade	Continued food system globalisation moves crops to locations with highest production efficiency.	1%	Increase in crop yields.
	9: Vertical and urban farms	Yield increases of 350 times have been suggested as possible (White, 2017).	1%	
	10: More multi-cropping and reduced fallows	Identified as potential route of increasing production (Alexandratos and Bruinsma, 2012; Ray and Foley, 2013)	2%	
Reducing losses	11: Harvest losses	Lower on farm losses through better harvest technology and control of pests and diseases.	5%	Reduction in associated losses.
	12: Transport and storage losses	Potential for gains due to current inefficiencies, particularly in lower income countries	5%	
	13: Processing losses	Increases in efficiencies of food processing.	5%	
	14: Retailer losses	Issues of sell-by/use-by dates, and selling 'imperfect' fruit/veg, especially in higher income countries.	5%	
	15: Consumer losses	Changes including lower consumer processing losses, e.g. peelings; less over-purchasing; and using leftovers.	5%	
	16: Household pets	Greater use of by-products or potentially a reduction in pet numbers or size of pets.	5%	Reduction in pet food.
	17: Food waste as feed	Directing food waste for uses as animal feed. Regulatory and potential health issues to consider.	2%	Increased animal production efficiency.
	18: Alternative feeds	Providing animal feeds from novel sources, such as algae or insects from waste (including human waste).	1%	
	19: Offal	Eating of offal, especially in some European countries and the US, could increase towards higher historic level.	2%	
Shifting diets	20: Vegetarian diets	Growing drive towards vegetarianism in higher income countries.	2%	Substitution of meat or animal products, respectively, for plant-based foods.
	21: Vegan diets	Similar to vegetarianism, veganism has recently become a mainstream movement in many countries.	1%	
	22: Low-meat diets	Global population who eat meat adopting a meat-free day (e.g. 'meat-free Friday').	3%	
	23: Over-consumption	The world is over-eating on average, with large distributional inequalities.	5%	Reduction of over-consumption.
	24: Insects	Adoption issues due to social acceptability in Western cultures, but already widely consumed in Asia.	1%	Substitution of current animal products with the alternative being considered, to provide equal protein.
	25: Cultured meat	Technological development still required and social acceptability not yet clearly demonstrated.	0.5%	
	26: Tofu	Established alternative to meat, making substantial future expansion less likely.	1%	
	27: Imitation meat	Substitutes are increasingly acceptable to consumers on taste, but production currently limited.	2%	
	28: Aquaculture	May be more socially acceptable than other meat alternatives, e.g. tastier and healthier.	2%	

	29: Monogastrics	Replacing red meat with chicken follows recent trends, with drivers including relative costs and health concerns.	3%	

Increasing production efficiency

Agricultural intensification, i.e. managing existing land more productively often using higher rates of other inputs, is often pitted against agricultural expansion as an alternative way of satisfying food demand (Foley et al., 2011). Large-scale uptake of agricultural production changes can often be constrained by a lack of investment in the adoption of new as well as existing technologies, leading to gaps between actual and achievable yields. Uptake is dependent on education and knowledge exchange to disseminate best practices globally, and whilst education and knowledge exchange programmes exist their effectiveness is unknown (Aker, 2011). Extensive changes in individual measures to increase production efficiency may be limited; however, the potential for marginal changes regarding production efficiency and the closure of yield gaps across a suite of measures could be high. We therefore outline ten aspects where marginal changes could increase production efficiency and thereby reduce agricultural land requirements.

Improved crop management practices to close yield gaps have been identified as strategies that could improve sustainability of the food system (Foley et al., 2011; Licker et al., 2010; Phalan et al., 2014; Van Ittersum et al., 2013). Achieved yields are limited by land management choices and access to a variety of inputs such as pesticides, machinery and nutrients (Godfray et al., 2010). With improved crop management practices yield gaps can be reduced (Alexandratos and Bruinsma, 2012; Foley et al., 2011) and as such we included increases in crop yields that could be attributed to this type of change (change 1). The 2% yield increase represents the closing the yield gap from West et al. (2014) by 7%, a rate 7 times smaller than assumed in that study. Progress in breeding and genetic techniques has also allowed for the development of high yielding crop varieties of many staple global crops (Jaggard et al., 2010; Tester and Langridge, 2010). Advances in crop breeding and genetic techniques over previous decades have therefore demonstrated the potential of such approaches (Jaggard et al., 2010; Tester and Langridge, 2010), although legislative change (e.g. relating to genetically modified organisms) may be required in some jurisdictions (Azadi and Ho, 2010; Reuter et al., 2010). We include improved crop breeding (change 2) and crop genetic modification (considered here to encompass genetic engineering and gene editing using techniques such as CRISPR-Cas9, change 3) as marginal changes leading to increased crop yields. For example, a metanalysis of literature from 1996 to 2016 showed that genetical engineered maize yields have increased by 10.1% compared to non-engineered varieties (Pellegrino et al., 2018). While substantially newer, improving yield performance is one of the main uses to which CRISPR-Cas9 gene editing has been applied (Ricroch et al., 2017).

The production efficiency of cropland could be increased globally through reductions of fallows and a greater area where multi-cropping is adopted, as both increase harvest areas without additional land. This is the continuation of an existing trend, where between 1961 and 2007, harvested land area grew four times faster than total standing cropland area, contributing to a 9% increase in global crop production (Ray and Foley, 2013). Alexandratos and Bruinsma(2012) suggest harvested areas in developing countries may increase by 130 Mha, around 14%, due to increased cropping intensities, aided by an increase in the share of irrigation in total arable land. Given that reduced fallows and multi-cropping could increase production without increasing agricultural area we consider this to be a marginal change (change 9). With a growing global urban population, urban farming has emerged as a strategy to achieve food security targets (Diekmann et al., 2018). This would in effect convert land previously frequently not used for food production (e.g. gardens and rooftops) into spaces that could become highly productive. Additionally, a number of fruit and vegetables are much higher yielding under the indoor controlled-environment technologies used in vertical farms (Despommier, 2013; Eigenbrod and Gruda, 2015), although their economics remains largely unproven. Both high- and low- tech forms of urban agriculture could increase production efficiency, generate land savings and reduce food miles (Eigenbrod and Gruda, 2015; Specht et al., 2014). 73 urban agriculture projects were identified in 2012 (Thomaier et al., 2014) with substantial continued research and public interest since (e.g., Grard et al., 2018; Othman et al., 2018; Wielemaker et al., 2019). Given the potential for urban agriculture to reduce agricultural land use, it was included as a marginal gain in this study (change 9). With continued globalisation of the food system, land requirements could decrease as production shifts to the most suitable locations. Furthermore improvements in infrastructure in developing countries, in particular rural roads, could greatly increase productivity and market access (Jouanjean, 2013). As such, we consider a marginal change that reflects improving trade and infrastructure resulting in greater production efficiency (change 8).

The global consumption of livestock products is expected to increase in the coming decades; any increases in production efficiency in the livestock sector could greatly contribute to creating a more sustainable food system. The livestock production sector has a history of increasing efficiency since the 1960s. For example, the efficiency of conversion of grain into meat in chickens and pigs has doubled (Herrero et al., 2010) and carcass weights have increased by 30% for both chicken and beef cattle (Bouwman et al., 2005; Thornton, 2010). Such productivity increases are a result of improved animal husbandry, livestock breeding and genetic techniques (Hayes et al., 2013; Thornton, 2010) and given their potential we included marginal changes that capture these processes. Marginal improvements in livestock husbandry practices (change 4), livestock breeding (change 5) and livestock genetic modification (change 6) all contribute to increasing production efficiency through improved feed conversion efficiencies. As with crops, genetic modification here considers both genetic engineering and gene editing, which either directly target improved yield traits or have an indirect impact on yields through disease resistance (Van Eenennaam, 2017). For example, reducing losses from African swine fever (Montoya et al., 2018) have been targeted through conveying resistance by gene editing (Petersen et al., 2018).

Reducing losses

Production efficiency is reduced by losses occurring throughout the food system: from harvest to consumption between a third and a half of crops are lost (Alexander et al., 2017b; Gustavsson et al., 2011). Large changes to improve the use of 'waste' streams may be infeasible as they will require legislation regarding the handling of waste (Salemdeeb et al., 2017), and the usage of alternative feeds may be hampered by a lack of investment into technologies to increase supply chain efficiency. Changes related to consumers and retailers rely on the effectiveness of campaigns raising awareness of food waste, limited by the complex cognitive mechanisms that define our motivations and dietary behaviours. Given these constraints, we therefore consider nine marginal changes that could reduce food system losses and agricultural land requirements.

Improving the sustainability of the food system may involve reassessing sources of feed for livestock; considering both the use of food waste (change 16) and alternative sources such as insects and algae as feed (change 17). In the European Union less than 3% of food waste is currently recycled as animal feed (zu Ermgassen et al., 2016) for the most part due to risks of contamination and disease concerns. However recycling food waste as feed is more widely practiced in Asian countries, in Japan for example 35.9% of food waste is used as feed (Salemdeeb et al., 2017), and if the EU was to adopt an Asian style recycling approach land use of EU pork alone could reduce by one fifth (zu Ermgassen et al., 2016)(Salemdeeb et al., 2017). The use of food waste as feed has been identified as a priority research area by the animal feed industry (Makkar and Ankers, 2014). It is widely recognised that feeding livestock soy or fishmeal has widespread environmental consequences and globally almost a third of crops harvested are used as feed (Steinfeld et al., 2006). There is also a growing interest in using insects as feed due to their nutritional characteristics; as a protein source, insects have been found to contain adequate amino acid compositions and antimicrobial peptides beneficial in feed (Gasco et al., 2018; Khan, 2018; Sánchez-Muros et al., 2014). Additionally, the use of insects as feed is expected to have beneficial environmental consequences (van Huis and Oonincx, 2017); insect production is efficient in terms of land use (Alexander et al., 2017a), insects have high feed conversion efficiencies (Premalatha et al., 2011; van Broekhoven et al., 2015) and some species can convert organic waste into high quality feed (Miech et al., 2016; van Broekhoven et al., 2015). Reassessing livestock feed sources is clearly a substantial way to increase sustainability by reducing losses and we therefore include marginal changes of this type.

At the consumer level considerable losses occur through discarded leftovers, inefficient food processing and overconsumption (Alexander et al., 2017b). Significant food system losses are associated with consumer behaviour (Alexander et al., 2017b; Gustavsson et al., 2011) and we therefore consider a marginal reduction in consumer-related losses as part of this analysis (change 14). Waste reduction throughout the food system could also be achieved by changing consumer attitudes, for example, we consider here marginal shifts towards a greater acceptance of consuming offal products (change 18) and 'imperfect' food products (change 13). In the fresh fruit and vegetable sector large volumes of products are unnecessarily wasted as they fail to meet quality standards, often aesthetic, set by consumers and retailers despite being safe and edible sources of food (Aschemann-Witzel et al., 2015; Plazzotta et al., 2017). Similarly, edible offal products are typically discarded (Henchion et al., 2016; Jayathilakan et al., 2012) however, the consumption of offal products could meet increasing demand for meat products without necessarily increasing livestock numbers given that up to 56% of the live weight of a beef animal can contain non-meat parts (Marti et al., 2011). More recently, consumer choices concerning the provision of edible food used for pet food has come under scrutiny. In China alone the land use for producing pet food has been estimated as between 43.6 and 151.9 Mha with considerable associated carbon emissions (Su et al., 2018). Evidently, reassessing the feeding of household pets could result in large land savings and we therefore include a marginal change in pet food consumption in our analysis (change 15).

Increasing supply chain efficiency is a further potential mechanism to reduce food system losses. Improving harvesting techniques that reduce spillage and mechanical damage and reducing pre-harvest losses such as agricultural residues and unharvested crops has the potential to improve food system efficiency greatly and we include this aspect as marginal change 10. In the storage and transportation sector food losses frequently occur due to poor refrigeration leading to spoiling. In developing countries poor storage is particularly troublesome with poor storage accounting for crop losses of up to 34% (Abass et al., 2014; Kimenju and De Groote, 2010; Zorya et al., 2011). As such, we consider a marginal change in the reduction of transport and storage losses (change 10). Losses during the processing of food commodities can also be considerable, with studies estimating losses of up to 59% during processing (Alexander et al., 2017b; Gustafsson et al., 2013); with fresh fruit and vegetable losses being particularly high in developing regions (Gustafsson et al., 2013). We consider a marginal change that represents improvements in processing of food commodities in this analysis (change 12). While the 5% rate for loss reductions chosen here is higher than for the other changes considered (Table 1), it is nonetheless lower, and consequently more achievable, than in previous studies (e.g. in Springmann et al. (2018) the 'medium' ambition for losses reduction is 50% and 'high' ambition is 75%).

Shifting diets

Dietary choices drive land use for food production; however, diets vary in terms of their environmental impacts depending primarily on the quantity of food consumed, and the proportion of animal products. Western diets, typically characterised by the high consumption of livestock products, tend to have the greatest environmental impacts in terms of land use requirements and greenhouse gas emissions (Buckwell and Nadeu, 2018; Poore and Nemecek, 2018; Tilman and Clark, 2014). Moreover, approximately one-third of global cereal crop production is used as livestock feed (Alexandratos and Bruinsma, 2012). Many argue that the sustainability of the food system would greatly improve with alternative diets, particularly the reduction of meat consumption (Alexander et al., 2017a; Machovina et al., 2015; Swain et al., 2018; Tilman and Clark, 2014; Wellesley et al., 2015; Willett et al., 2019). However, the cultural and economic importance of diets may prevent transformation in the food system though large shifts in consumption choices. It is likely that any widespread policy actions to reduce meat consumption, particularly in developing countries when sufficient protein is often lacking, would be met with widespread disapproval. Similarly, technological development and social acceptance hamper large increases in the consumption of cultured meat, insects and imitation meat (Bhat et al., 2017; Moritz et al., 2015; van Huis, 2013) . We therefore consider a range of individual marginal dietary changes that combined may be a more feasible pathway to transform the food system.

In high-income countries, the movement towards vegan and vegetarian diets is growing as consumers become increasingly aware of the negative environmental and health consequences related to the consumption of animal products. In the UK alone, the market for meat-free foods increased by 6% between 2015 and 2017 (MINTEL, 2017). Furthermore, while consumers may not opt to switch entirely to vegetarian or vegan diets and increasing numbers in developed countries are adopting reduced-meat or 'flexitarian' diets that include for example 'meat free Mondays'. Recent studies quantifying the benefits of reduced meat consumption have reported potential greenhouse gas emission and agricultural land use reductions of up to 70% (Aleksandrowicz et al., 2016; Tilman and Clark, 2014), with vegan diets providing the greatest reductions. The production of ruminants is particularly detrimental to the environment, with beef and cattle milk production respectively contributing 41% and 20% of the livestock sector emissions (Gerber et al., 2013). With this in mind, replacing ruminant meat with other types such a pork and poultry could deliver environmental benefits. Wirsenius, Azar, & Berndes (2010) found land savings of up to 24% in a ruminant meat substitution scenario, albeit land savings were still lower than a vegetarian scenario, and diets high in eggs and poultry meat have higher land use efficiency (Alexander et al., 2017a). Widespread global changes in animal product consumption to bring environmental benefits is unlikely, but small changes are still effective and we consider marginal increases in vegetarianism (change 20), veganism (change 21), low meat diets (change 22) and the replacement of red meat with poultry (change 29).

The market for other meat substitutes such as imitation meat, tofu and aquaculture has grown in recent years (MINTEL, 2014) however substitutes such as insects and cultured meat are less socially accepted. However, uptake of alternative protein sources could reduce agricultural land areas. Indeed significant land saving potential were shown by replacing 50% of animal products with other protein sources (Alexander et al., 2017a); with imitation meat and insect consumption demonstrating the greatest land use efficiency. Owing to the potential of such alternatives, despite their non-mainstream reputation, we include marginal changes that reflect small increases in the uptake of insect consumption (change 24), cultured meat consumption (change 25), tofu consumption (change 26), imitation meat consumption (change 27) and aquaculture consumption (change 28).

The type of food consumed is often the focus of studies exploring the environmental impact of dietary choices however; overconsumption, particularly in the developed world, is also an important factor. Indeed overconsumption has been found to be at least as large a contributor to losses as other types of consumer waste(Gustavsson et al., 2011) and ‘healthy diet’ scenarios that effectively reduce over consumption have demonstrated significant land use and greenhouse gas emission savings could be made if over consumption is addressed (Bajželj et al., 2014; Green et al., 2015). To account for the importance of changing the quantity of food consumed we include a marginal change that reduces overconsumption (change 23).

3 Methods

The identified marginal changes (Table 1) act to increase yields, reduce losses, decrease consumption per capita, or adjust the commodities consumed. Average production efficiencies (areas required per unit mass of food) and diets in 7 world regions were considered in terms of cropland for food, cropland for feed and pasture for 90 commodities. Constant population was assumed, with diets and yields adjusted only to reflect the marginal changes considered. The magnitude of each change is based on what may be achievable in the short to medium term and represents a cumulative change rate in each case, i.e., they are not annual rates. The objective is to explore the magnitude of net transformation from the identified marginal changes, rather than to be predictive for a particularly year.

A 2013 baseline was used, the most recent year for which the required data were available (FAOSTAT, 2018b, 2018c, 2018a, 2018d, 2018e, 2018f, 2018g). Crop areas were allocated to the use of each crop (e.g. food or feed) from FAOSTAT (2018f, 2018d) commodity balance sheet data. To account for quantities of crops processed (e.g. soyabeans), areas used to produce those quantities were allocated by economic value between the resulting commodities (e.g. soyabean oil and meal). Monogastric species were allocated their feed requirement from the total FAO feed quantities. These feed requirements were calculated by multiplying the quantity of animal product produced by their feed conversion ratio (Alexander et al., 2016). Ruminant-derived products were then allocated the remaining feed pro rata by feed requirement, with remaining nutrition assumed to be derived from pasture. Pasture areas were allocated between ruminant products by feed requirements using the same feed requirement ratios.

The resultant country level data were aggregated into the 7 world regions used by Gustavsson et al. (2011), weighted by current production quantity, and used to calculate a mean production efficiency for each commodity and region. For animal products these efficiencies expressed the area requirements for feed and pasture per unit of mass. Similarly, baseline regional diets were determined from weighted commodity balance data (2018f, 2018d). Loss rates and methodology from Gustavsson et al. (2011) were used to estimate regional losses per food system stage (i.e. commodity for agricultural product, handling and storage, processing, distribution, and consumer waste). Losses due to over-consumption were also estimated by comparing human nutritional requirements with the quantities consumed after accounting for previous stage losses, following Alexander et al. (2017b). Regional food supply requirements were converted to areas using global production efficiency, thereby accounting for imports and exports and providing a more comparable dietary footprint between regions.

This representation allows the agricultural land use implications from the changes considered to be calculated by adjusting different aspects of the food system. In the baseline case, summing across all commodities and regions the unadjusted demand (accounting for losses) multiplied by the unadjusted production efficiencies reproduces the global FAO global pasture areas and crop areas used for food and feed. Changes that improve crop production yields (changes 1-3, 8 and 9) were represented by the same change in production efficiencies, i.e. reducing the required area per unit of food or feed. Similarly, for pasture yield improvements (change 4) reduces the area required for ruminant products for pasture. Changes impacting animal feed conversion ratios (changes 5-7 and 17-19) were applied as a reduction in feed and pasture area requirements for animal products. Rates of losses changes (11-16 and 23) act on the rates of losses calculated above, adjusted by the rate of marginal gain action. Dietary changes (20-22 and 24-29) adjust the regional demand with resultant diets applied to regional populations to calculate required food supplies. Changes involving substitution between foods were applied so as to maintain a constant protein quantity in the diet (Alexander et al., 2016). In the case of new foods or production systems (e.g. insects, cultured meat and aquaculture) feed requirements are derived from feed conversion ratios (Alexander et al., 2017a). Therefore, these commodities are all assumed to be produced from feed grown for the purpose with the associated land requirements not from waste streams. Changes are applied as multiplicative factors to the relevant quantities and, therefore, multiple changes affecting the same quantity have a compounded impact.

To explore sensitivities to variation in the adoption rates considered, the rates of change were adjusted by a factor of 0.5 and 2, respectively, to give 'low' and 'high' change conditions. Additionally, a Monte Carlo approach, with 1000 samples, was used with factors from 0 to 2 drawn from a uniform distribution applied independently to each marginal change rate.

4 Results

In 2013, 93.7% (4576 Mha) of the 4884 Mha of agricultural areas were appropriated by the food system. The remaining agricultural areas were associated with the production of crops for fibre and bioenergy. Therefore, 35.2% of the 13 billion ha global land surface is used for food production. This corresponds to a global average of 0.63 ha per person.

How might this land area change under the concept of marginal gains? Country level changes were aggregated to seven global regions; high and medium income countries to Europe; North America & Oceania and Industrialized Asia regions and the lower income countries to sub-Saharan Africa; North Africa, Western & Central Asia; South & Southeast Asia and Latin America[58]. The combined effect of the 29 marginal changes considered here reduced the land requirement for food production in each of these regions, from 109 Mha in sub-Saharan Africa to 157 Mha in Europe (Figure 1a). Considerable differences in the proportions of reductions from supply and consumer changes were evident between regions. The majority of European, North America and Oceania land use reductions were related to consumer choices (63% and 64%, respectively). Conversely, sub-Saharan Africa and North Africa, West and Central Asia had lower proportion of gains from consumer choices (33% and 35% respectively), with the majority of land area reductions arising from production and supply chain improvements. The area required per person for food also showed considerable variation between regions (Figure 1b). North America and Oceania had the highest current per capita areas of (1.46 ha/person), which drops by 25% to 1.09 ha/person under the marginal gains. South and South East Asia has the lowest areas for food per capita (initially 0.28 ha/person), which declines by the lowest of any region in absolute and percentage terms, to 0.24 ha/person; a 16% reduction.

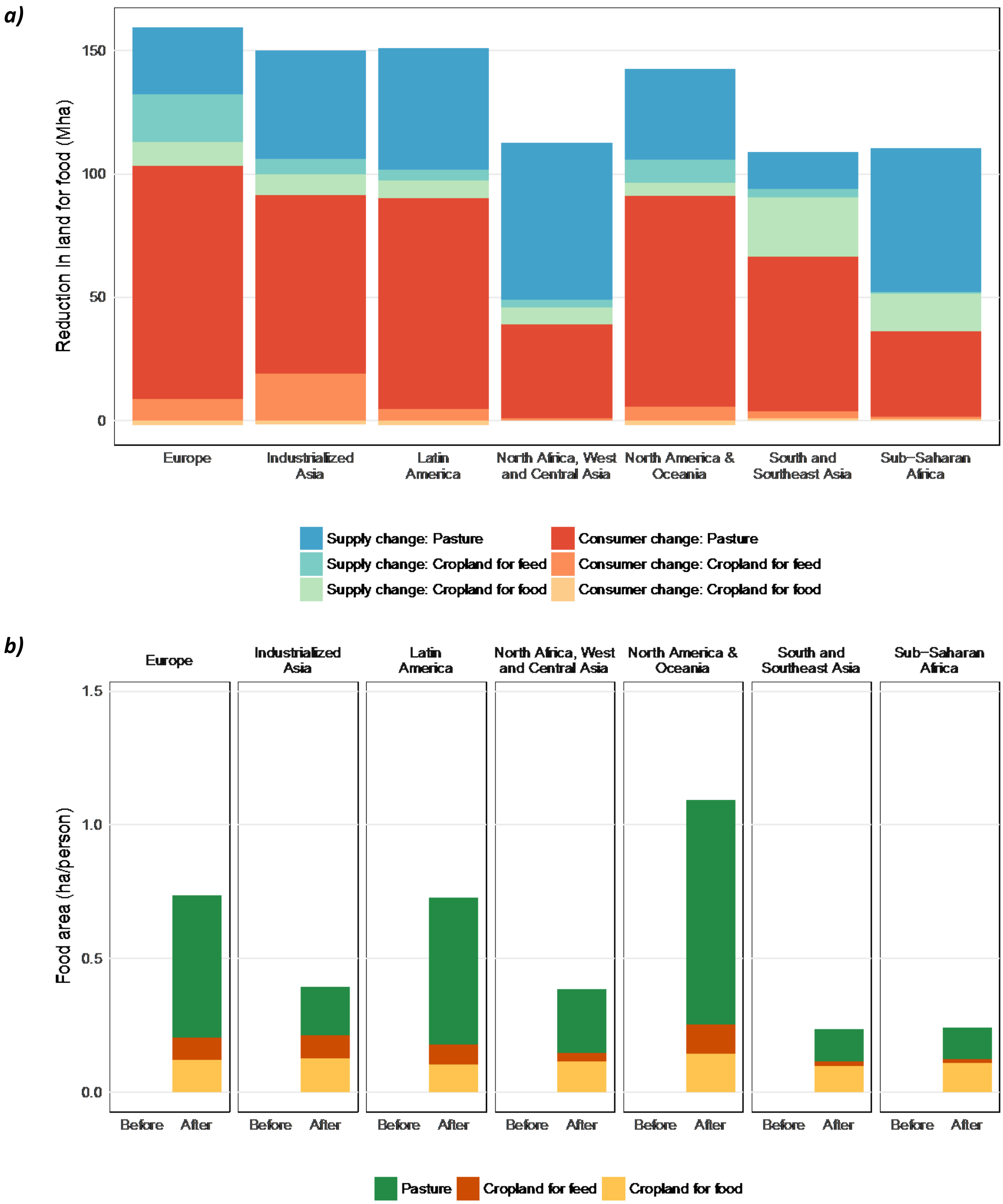

Figure 1. Combined effects, by region, of marginal food system gains in pasture, cropland for feed and cropland for food areas, a) reduction in area of land required for food divided into supply and consumer changes; and, b) area per person for food.

The total global land area required for food was found to reduce by 947 Mha (a 21% reduction) to 3629 Mha (or 27.9% of the global land surface) when all marginal changes were applied at their default rates (Figure 2a). This total reduction comprised a 24% (118 Mha) reduction in cropland for feed, a 23%

reduction in pasture (755 Mha), but only an 8% (74 Mha) reduction in cropland for food. Reducing the change rates by half ('low' case, Figure 2a) gave a total reduction of 502 Mha (11%), while doubling the rates ('high' case, Figure 2a) gave a reduction of 1691 Mha (37%) to 2885 Mha, an agricultural area not seen since before the 1800s (Ramankutty and Foley, 1999). Such changes would reduce average land for food production per person to 0.40 – 0.56 ha. Stochastic sampling of the marginal change rates (from values between 0 and 2%) gave probability distributions of land area reductions within a similar range, as shown in Figure 3.

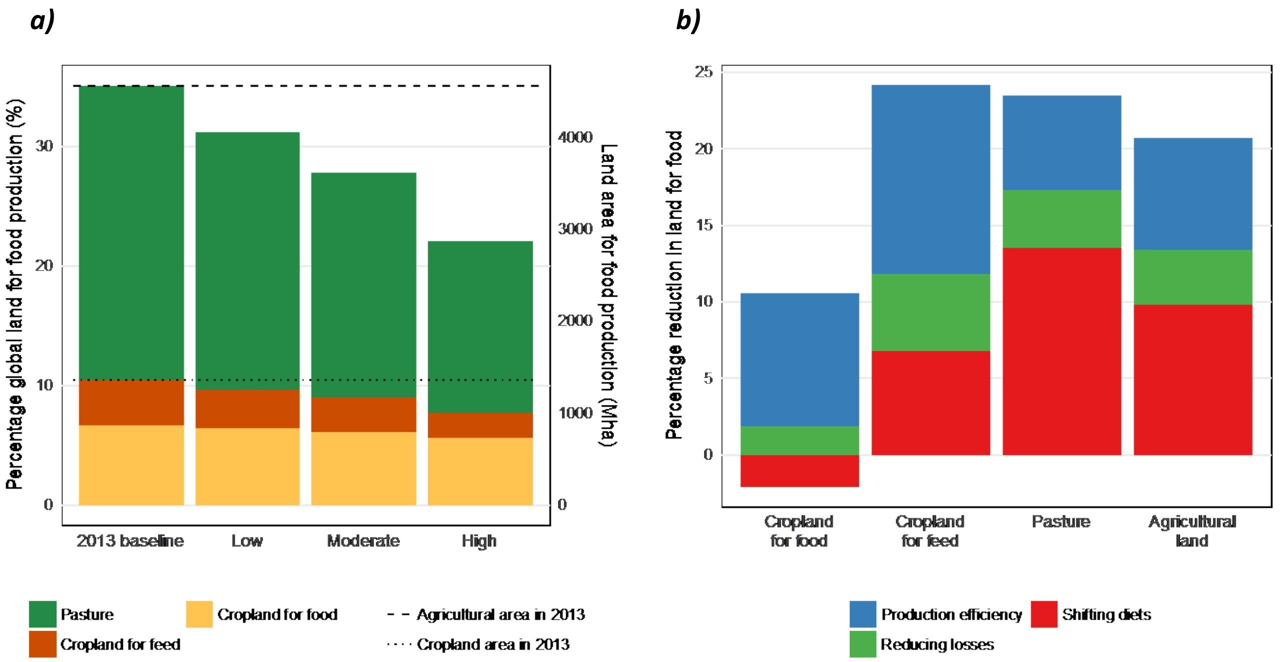

Figure 2. Global areas of pasture, cropland for feed and cropland for food a) from the combined effects of all 29 marginal gains considered, by rate (i.e. low, moderate and high), and b) percentage reductions with moderate rates by type of marginal change.

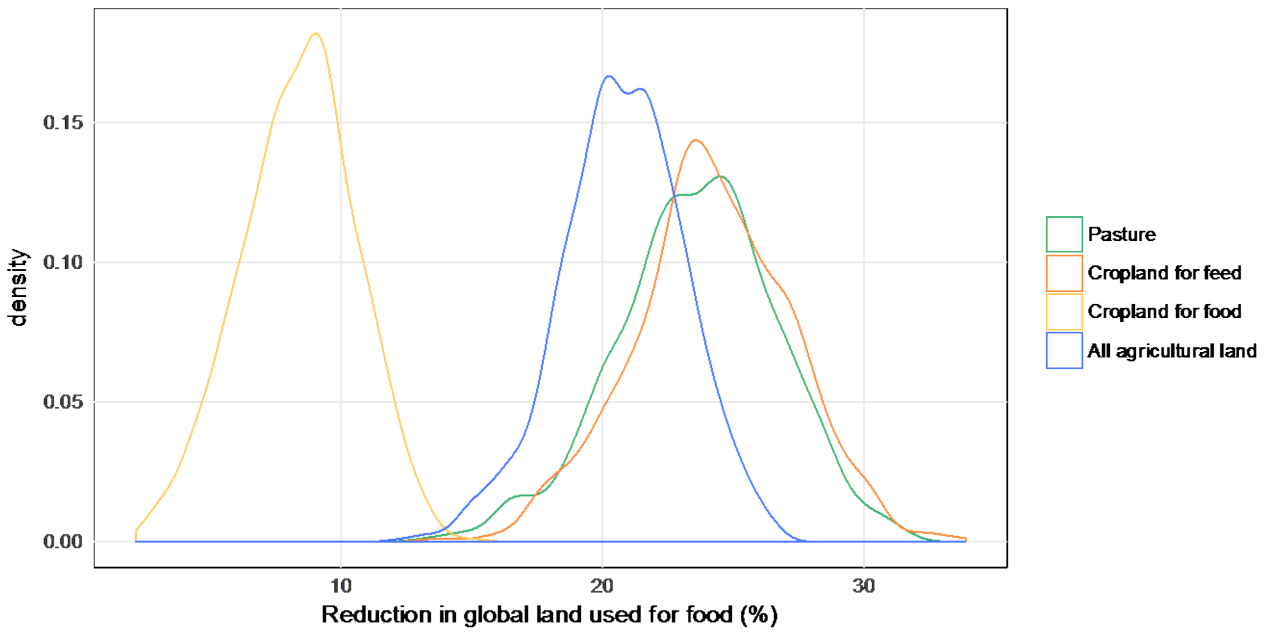

Figure 3: Sampled reduction in land used for food production, from 1000 randomly selected marginal change rates from a multiple of 0 to 2 times that of the assumed rate (Table 1).

The 3 categories of change (increasing production efficiency, reducing losses and shifting diets) produce different proportional effects on land use types (Figure 2b). Pasture area reductions are mainly (58%) attributable to dietary shifts, with a further 16% from reducing losses and 26% from production efficiencies. Conversely, dietary shifts were associated with an increase in cropland food, as animal products are substituted for diets with a greater fraction of plant-based foods. Area reductions of cropland for animal feed were approximately half (51%) due to production efficiencies, with 21% from reducing losses and 28% from dietary shifts. The net effect for total agricultural land area was more balanced, with 48% of the reduction caused by shifting diets, 35% by production efficiencies and 17% from reducing losses.

Individual marginal gains lead to different levels of cropland and pasture change (Figure 4). This figure shows in more detail the opposing effects of certain dietary changes on cropland and pasture. For example, substituting ruminant products with monogastric products decreases pasture area, but increases animal feed requirements from cropland. Substitution of a proportion of livestock products with greater plant-based diets (e.g. vegetarianism and veganism) decreases pasture area, but increases cropland for food. Advances in livestock production and pasture management caused the largest area reductions of all production efficiency changes. Greater consumption of offal caused the largest area reduction of all reducing loss changes, while low meat diets and monogastrics caused the largest area reduction of all shifting diet changes. However, implicit in these observed changes are the assigned rates of action (Table 1).

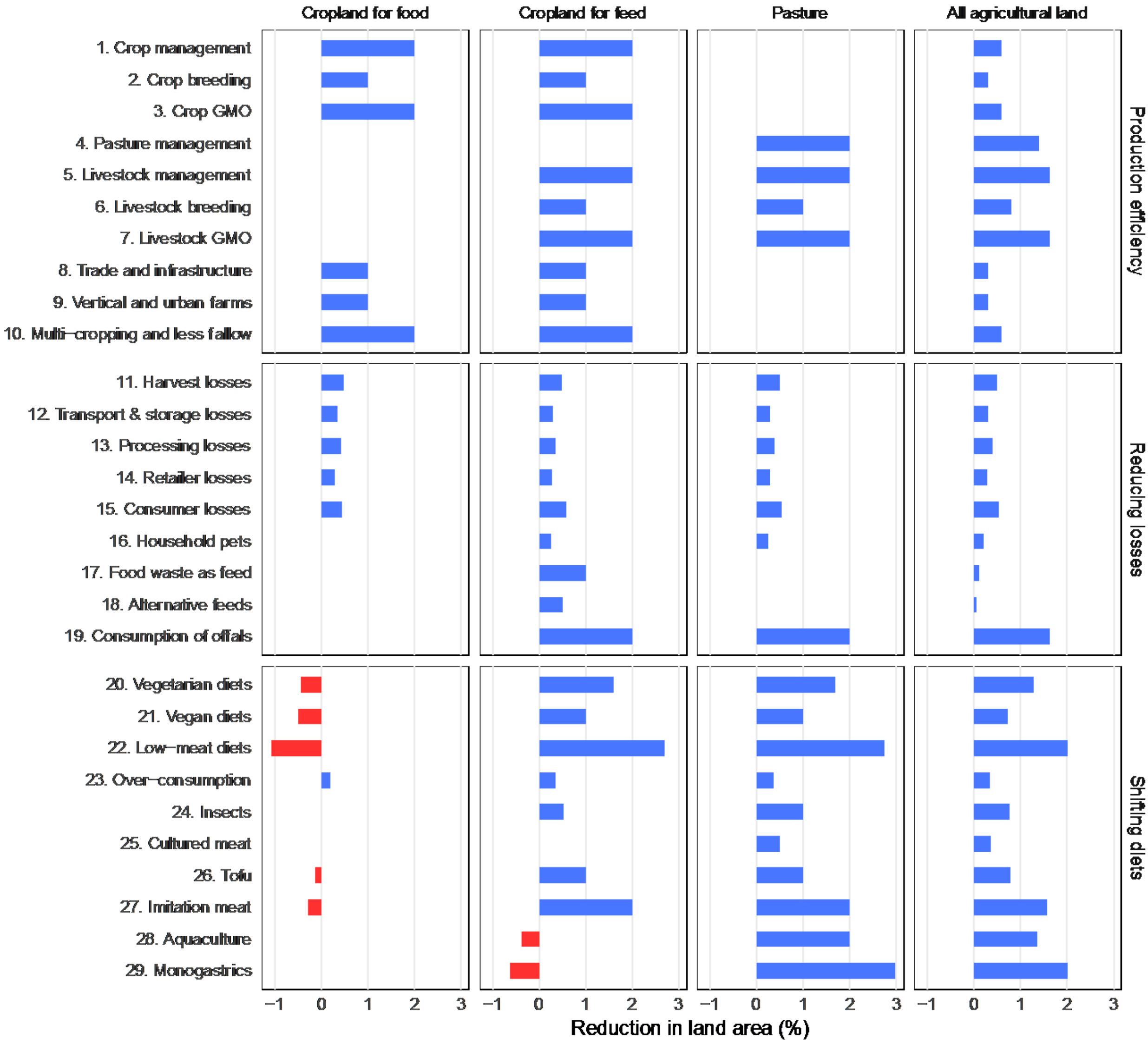

Figure 4. Percentage reduction in global land used by the food system from single marginal changes.

5 Discussion

There is a pressing need to understand how humanity could transform the global food system in ways that would minimise environmental degradation, whilst satisfying the nutritional requirements of the global population. The concept of marginal gains suggests that transformation need not necessarily result from sudden or large changes in existing systems. Application of the marginal gains concept to the global food system shows that the land area used for food production could be reduced considerably (by up to 37% of the current agricultural area) through changes that are plausibly achievable now. The 29 marginal gains selected here encompass some of the most discussed potential changes to the food system, such as increases in yields due to biotechnology, as well as some less recognised possibilities, such as decreasing the quantity of livestock products that are fed to pets. The magnitude of this effect is comparable to those identified by previous studies focusing on a few major, non-marginal and, as a result, less plausible changes to the food system (Alexander et al., 2017a, 2016; Röös et al., 2017; Willett et al., 2019).

Particularly notable is the scope for meat consumption allowed by the marginal gains approach, despite the large land footprint of livestock production. This result aligns with the suggestion that some pastures are, in terms of agricultural production, unsuitable for anything other than the rearing of ruminant livestock (Röös et al., 2016), but contrasts with suggestions that substantial reductions in consumption of animal source foods are necessary to achieve environmental sustainability (Willett et al., 2019). Pasture is also important for biodiversity and for the livelihoods of minority groups such as nomadic pastoralists who rely on livestock for most of their nutrient intake (Eisler et al., 2014). However, the approach presented here did not account for the impact of greenhouse gas emissions from livestock production on climate change, which will impact on future agricultural productivity (Schmidhuber and Tubiello, 2007; Steinfield, 2006). Neither did it consider animal welfare across the marginal gains related to increased livestock production efficiencies or the replacement of ruminant livestock with monogastrics or aquaculture. Thus, evaluating changes in livestock production requires a rigorous and widespread analysis of the environmental and ethical impacts of production.

Historically, changes to the food system that have increased production have not necessarily resulted in reductions in land area. This is due to the 'rebound effect', where increasing efficiency increases affordability of certain agricultural products leading to greater demand, sometimes termed a Jevons effect (Amado and Sauer, 2012; Chan and Gillingham, 2015). The profits from fulfilling this increased demand drive agricultural expansion, rather than reduction. Such rebound effects have occurred with the production of soybean in Brazil, and oil palm in Indonesia and Malaysia (Lambin and Meyfroidt, 2011). Another concern is the abandonment of agricultural land without restoration, which can increase the risk of erosion, wildfire, and general landscape degradation. In Europe, for example, abandonment of agricultural land now threatens between 5-65% of important bird habitats (Stoate et al., 2009).

Nevertheless, when land gains are realised, they can significantly improve the prospects for biodiversity conservation, and the supply of ecosystem services. The need for the preservation of large swathes of intact natural landscapes for species conservation is becoming increasingly apparent, especially for endangered species with small ranges (Balmford et al., 2005; Phalan et al., 2016, 2011). The land areas that might be spared due to marginal gains are large enough to generate very substantial benefits for biodiversity (Dinerstein et al., 2017). However, further work is required to reconcile the spatial generality of the calculated effects of global marginal changes with the need for large, region-specific reductions in agricultural land to prevent the degradation of the most valuable ecosystems such as tropical rainforest. This will depend on ensuring that various political and cultural institutions have measures in place to balance the trade-offs arising from changes within the food system, and to support the maintenance of the land spared for nature. Political interventions may also have unintended environmental outcomes, for example recent US-China trade conflicts have shifted international trade in soy, potentially leading to agricultural expansion and large-scale deforestation in the tropics (Fuchs et al., 2019).

Reductions in land used for food differ widely between regions, especially between low and high-income regions. The benefits of marginal gains in high-income countries were mostly through the consumption changes, highlighting the need for alterations in consumption patterns within these regions. In particular, Europe, North America and Oceania could play an important leadership role in improving consumer choices, especially concerning overconsumption, the dietary mix and other wastes and losses in the system. The benefits of marginal gains in low-income countries were stronger on the production-side of the food system. This implies a need to support food producers in changing the efficiency of food production and distribution, e.g. through improved infrastructure, access to capital, or farmer advisory services (FAO, 2013).

The marginal gains approach has considerable utility for decision-making and policy implementation, since marginal gains reflect policy preferences for incremental change (Dunn et al., 2017; Mapfumo et al., 2017). However, it is critical to understand that the benefits offered by marginal gains cannot be achieved without considerable and concerted action across multiple policy sectors. Implementing marginal gains is not the easy option, to which we are sure Dave Brailsford would attest: it marks, however, a feasible and tractable pathway to transformation. It is not a license for inaction, but a call to arms for what might be achieved with appropriate policy intervention and societal change.

6 Conclusions

Land is central to the food system, and its profligate appropriation has caused significant environmental damage, largely due to mismanagement of agricultural and natural ecosystems and wasteful human behaviour. Because of this, there have been multiple calls for transformation in the global food system, but with no clear roadmaps for achieving this aspiration. Large-scale changes in the food system are obstructed by political and public inertia and a tendency towards incremental change. For example, public acceptability of the EAT–Lancet reference diet remains questionable. However, we show here that transformation can also occur through simultaneous action on the multiple factors that underpin food systems. The relatively smaller shift in each factor reduces potential barriers to adoption, in comparison to the larger-scale change more typically proposed. It is important to recognise that even achieving marginal gains requires considerable and coordinated efforts across policy sectors. Nonetheless, acting collectively plausible marginal changes can reduce global land areas used for food production substantially, up to 37% under the assumptions used here, suggesting that such an approach may lead to an achievable food system transformation.

7 References

Abass, A.B., Ndunguru, G., Mamiro, P., Alenkhe, B., Mlingi, N., Bekunda, M., 2014. Post-harvest food losses in a maize-based farming system of semi-arid savannah area of Tanzania. Journal of Stored Products Research 57, 49–57. doi:https://doi.org/10.1016/j.jspr.2013.12.004

Aker, J.C., 2011. Dial “A” for agriculture: a review of information and communication technologies for agricultural extension in developing countries. Agricultural Economics 42, 631–647. doi:10.1111/j.1574-0862.2011.00545.x

Aleksandrowicz, L., Green, R., Joy, E.J.M., Smith, P., Haines, A., 2016. The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. Plos One 11, e0165797. doi:10.1371/journal.pone.0165797

Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D., Rounsevell, M., 2017a. Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? Global Food Security 15, 22–32. doi:10.1016/j.gfs.2017.04.001

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., Rounsevell, M.D.A., 2017b. Losses, inefficiencies and waste in the global food system. Agricultural Systems 153, 190–200.

Alexander, P., Brown, C., Rounsevell, M., Finnigan, J., Arneth, A., 2016. Human appropriation of land for food: The role of diet. Global Environmental Change 41, 88–98.

Alexander, P., Rabin, S., Anthoni, P., Henry, R., Pugh, T.A.M., Rounsevell, M.D.A., Arneth, A., 2018. Adaptation of global land use and management intensity to changes in climate and atmospheric carbon dioxide. Global Change Biology 24, 2791–2809. doi:10.1111/gcb.14110

Alexander, P., Rounsevell, M.D.A., Dislich, C., Dodson, J.R., Engström, K., Moran, D., 2015. Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. Global Environmental Change 35, 138–147. doi:10.1016/j.gloenvcha.2015.08.011

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision 160.

Alroy, J., 2017. Effects of habitat disturbance on tropical forest biodiversity. Proceedings of the National Academy of Sciences 114, 6056–6061. doi:10.1073/pnas.1611855114

Amado, N.B., Sauer, I.L., 2012. An ecological economic interpretation of the Jevons effect. Ecological Complexity 9, 2–9. doi:10.1016/j.ecocom.2011.10.003

Aschemann-Witzel, J., de Hooge, I., Amani, P., Bech-Larsen, T., Oostindjer, M., 2015. Consumer-Related Food Waste: Causes and Potential for Action. Sustainability 7, 6457–6477. doi:10.3390/su7066457

Azadi, H., Ho, P., 2010. Genetically modified and organic crops in developing countries: A review of options for food security. Biotechnology Advances 28, 160–168. doi:https://doi.org/10.1016/j.biotechadv.2009.11.003

Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E., Gilligan, C. a., 2014. Importance of food-demand management for climate mitigation. Nature Climate Change 4, 924–929. doi:10.1038/nclimate2353

Balmford, A., Green, R.E., Scharlemann, J.P.W., 2005. Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. Global Change Biology 11, 1594–1605. doi:10.1111/j.1365-2486.2005.001035.x

BBC News, 2015. Should we all be looking for marginal gains? [WWW Document]. URL https://www.bbc.co.uk/news/magazine-34247629 (accessed 10.1.18).

Bhat, Z.F., Kumar, S., Bhat, H.F., 2017. In vitro meat: A future animal-free harvest. Critical Reviews in Food Science and Nutrition 57, 782–789. doi:10.1080/10408398.2014.924899

Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., Soenario, I., 2005. Exploring changes in world ruminant production systems. Agricultural Systems 84, 121–153. doi:10.1016/j.agsy.2004.05.006

Bowles, N., Alexander, S., Hadjikakou, M., 2019. The livestock sector and planetary boundaries : A ‘ limits to growth ’ perspective with dietary implications. Ecological Economics 160, 128–136. doi:10.1016/j.ecolecon.2019.01.033

Brown, C., Alexander, P., Arneth, A., Holman, I., Rounsevell, M., 2019. Achievement of Paris climate goals unlikely due to time lags in the land system. Nature Climate Change 9, 203–208. doi:10.1038/s41558-019-0400-5

Buckwell, A., Nadeu, E., 2018. What is the Safe Operating Space for EU livestock? RISE Foundation, Brussels.

Butler, R.A., Laurance, W.F., 2009. Is Oil Palm the Next Emerging Threat to the Amazon? Tropical Conservation Science 2, 1–10. doi:10.1177/194008290900200102

Chan, N.W., Gillingham, K., 2015. The Microeconomic Theory of the Rebound Effect and its Welfare Implications. Journal of the Association of Environmental & Resource Economists Abstract 2, 133–159. doi:10.1071/AR9620031

Delgado, C.L., 2003. Rising consumption of meat and milk in developing countries has created a new food revolution. The Journal of Nutrition 133, 3907S-3910S.

Despommier, D., 2013. Farming up the city: the rise of urban vertical farms. Trends in biotechnology 31, 388–389.

Diekmann, L.O., Gray, L.C., Baker, G.A., 2018. Growing ’good food’ : urban gardens , culturally acceptable produce and food security.

Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N.D., Wikramanayake, E., Hahn, N., Palminteri, S., Hedao, P., Noss, R., Hansen, M., Locke, H., Ellis, E.C., Jones, B., Barber, C.V., Hayes, R., Kormos, C., Martin, V., Crist, E., Sechrest, W., Price, L., Baillie, J.E.M., Weeden, D., Suckling, K., Davis, C., Sizer, N., Moore, R., Thau, D., Birch, T., Potapov, P., Turubanova, S., Tyukavina, A., De Souza, N., Pintea, L., Brito, J.C., Llewellyn, O.A., Miller, A.G., Patzelt, A., Ghazanfar, S.A., Timberlake, J., Klöser, H., Shennan-Farpón, Y., Kindt, R., Lillesø, J.P.B., Van Breugel, P., Graudal, L., Voge, M., Al-Shammari, K.F., Saleem, M., 2017. An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. BioScience 67, 534–545. doi:10.1093/biosci/bix014

Dunn, M., Rounsevell, M.D., Carlsen, H., Dzebo, A., Lourenço, T.C., Hagg, J., 2017. To what extent are land resource managers preparing for high-end climate change in Scotland? Climatic Change 141, 181–195. doi:10.1007/s10584-016-1881-0

Eigenbrod, C., Gruda, N., 2015. Urban vegetable for food security in cities. A review. Agronomy for Sustainable Development 35, 483–498. doi:10.1007/s13593-014-0273-y

Eisler, M.C., Lee, M.R.F., Tarlton, J.F., Martin, G.B., Beddington, J., Dungait, J.A.J., Greathead, H., Liu, J., Mathew, S., Miller, H., Misselbrook, T., Murray, P., Vinod, V.K., Van Saun, R., Winter, M., 2014. Agriculture: Steps to sustainable livestock. Nature 507, 32–34.

FAO, 2013. Save and grow - a policymaker’s guide to the sustainable intensification of smallholder crop production. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAOSTAT, 2018a. Resources/Land (2018-09-24). Food and Agriculture Organization of the United Nations, Rome, Italy.

FAOSTAT, 2018b. Food Supply - Livestock and Fish Primary Equivalent (2018-09-24). Food and Agriculture Organization of the United Nations, Rome, Italy.

FAOSTAT, 2018c. Production/Livestock Primary (2018-09-24). Food and Agriculture Organization of the United Nations, Rome, Italy.

FAOSTAT, 2018d. Commodity Balances/Livestock and Fish Primary Equivalent (2018-09-24). Food and Agriculture Organization of the United Nations, Rome, Italy.

FAOSTAT, 2018e. Production/Crops (2018-09-24). Food and Agriculture Organization of the United Nations, Rome, Italy.

FAOSTAT, 2018f. Commodity Balances/Crops Primary Equivalent (2018-09-24). Food and Agriculture Organization of the United Nations, Rome, Italy.

FAOSTAT, 2018g. Food Supply - Crops Primary Equivalent (2018-09-24). Food and Agriculture Organization of the United Nations, Rome, Italy.

Foley, J. a, Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E. a, Kucharik, C.J., Monfreda, C., Patz, J. a, Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science (New York, NY) 309, 570–4. doi:10.1126/science.1111772

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–42. doi:10.1038/nature10452

Foresight, 2011. The Future of Food and Farming, Final Project Report. The Government Office for Science, London.

Fuchs, R., Alexander, P., Brown, C., Cossar, F., Henry, R., Rounsevell, M., 2019. US–China trade war imperils Amazon rainforest. Nature 567, 451–454.

Gasco, L., Finke, M., Van Huis, A., 2018. Can diets containing insects promote animal health?

Gerber, P.J.P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Food and Agriculture Organization of the United Nations (FAO), Rom.

Godfray, H.C.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough, P., Springmann, M., Jebb, S.A., 2018. Meat consumption, health, and the environment. Science 361, eaam5324. doi:10.1126/science.aam5324

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science (New York, NY) 327, 812–8. doi:10.1126/science.1185383

Görg, C., Brand, U., Haberl, H., Hummel, D., Jahn, T., Liehr, S., 2017. Challenges for Social-Ecological Transformations : Contributions from Social and Political Ecology 1–21. doi:10.3390/su9071045

Grard, B.J., Chenu, C., Manouchehri, N., Houot, S., Frascaria-lacoste, N., Aubry, C., 2018. Rooftop farming on urban waste provides many ecosystem services.

Green, R., Milner, J., Dangour, A.D., Haines, A., Chalabi, Z., Markandya, A., Spadaro, J., Wilkinson, P., 2015. The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change. Climatic Change 129, 253–265. doi:10.1007/s10584-015-1329-y

Grooten, M., Almond, R.E.A. (Eds., 2018. Living Planet Report - 2018: Aiming Higher. WWF, Gland, Switzerland.

Gustafsson, J., Cederberg, C., Sonesson, U., Emanuelsson, A., 2013. The methodology of the FAO study: Global Food Losses and Food Waste-extent, causes and prevention"-FAO, 2011. SIK Institutet för livsmedel och bioteknik.

Gustavsson, J., Cederberg, C., Sonesson, U., Otterdijk, R. van, Meybeck, A., 2011. Global food losses and food waste– Extent, causes and prevention. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-being. Ecosystem Ecology: a new synthesis 1, 110–139.

Hayes, B.J., Lewin, H.A., Goddard, M.E., 2013. The future of livestock breeding: genomic selection for efficiency, reduced emissions intensity, and adaptation. Trends in Genetics 29, 206–214. doi:https://doi.org/10.1016/j.tig.2012.11.009

Henchion, M., McCarthy, M., O'Callaghan, J., 2016. Transforming Beef By-products into Valuable ingredients: Which spell/recipe to Use? Frontiers in nutrition 3, 53.

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-Livestock Systems. Science 327, 822 LP – 825.

Jaggard, K.W.W., Qi, A., Ober, E.S.S., 2010. Possible changes to arable crop yields by 2050. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2835–2851. doi:10.1098/rstb.2010.0153

Jayathilakan, K., Sultana, K., Radhakrishna, K., Bawa, A.S., 2012. Utilization of byproducts and waste materials from meat, poultry and fish processing industries: A review. Journal of Food Science and Technology 49, 278–293. doi:10.1007/s13197-011-0290-7

Jouanjean, M., 2013. Foster Agricultural Trade and Market Integration in Developing Countries: an Analytical Review. London: Overseas Development Institute pp1-26.

Kates, R.W., Travis, W.R., Wilbanks, T.J., 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. Proceedings of the National Academy of Sciences 109, 7156–7161. doi:10.1073/pnas.1115521109

Khan, S.H., 2018. Recent advances in role of insects as alternative protein source in poultry nutrition. Journal of Applied Animal Research 46, 1144–1157. doi:10.1080/09712119.2018.1474743

Kimenju, S.C., De Groote, H., 2010. Economic analysis of alternative maize storage technologies in Kenya, in: Joint 3rd African Association of Agricultural Economists (AAAE) and 48th Agricultural Economists Association of South Africa (AEASA) Conference, Cape Town, South Africa, September. pp. 19–23.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change , economic globalization , and the looming land scarcity. Proceedings of the National Academy of Sciences of the United States of America 108, 3465–3472. doi:10.1073/pnas.1100480108

Licker, R., Johnston, M., Foley, J.A., Barford, C., Kucharik, C.J., Monfreda, C., Ramankutty, N., 2010. Mind the gap: how do climate and agricultural management explain the 'yield gap'of croplands around the world? Global ecology and biogeography 19, 769–782.

Machovina, B., Feeley, K.J., Ripple, W.J., 2015. Biodiversity conservation: The key is reducing meat consumption. Science of the Total Environment 536, 419–431. doi:10.1016/j.scitotenv.2015.07.022

Makkar, H.P.S., Ankers, P., 2014. Towards sustainable animal diets: a survey-based study. Animal Feed Science and Technology 198, 309–322.

Mapfumo, P., Onyango, M., Honkponou, S.K., Mzouri, E.H. El, Githeko, A., Rabeharisoa, L., Obando, J., Omolo, N., Majule, A., Denton, F., Ayers, J., Agrawal, A., 2017. Pathways to transformational change in the face of climate impacts: an analytical framework. Climate and Development 9, 439–451. doi:10.1080/17565529.2015.1040365

Marti, D., Johnson, R.J., Mathews, K.H., 2011. Where's the (not) Meat?: Byproducts from Beef and Pork Production. US Department of Agriculture.

Miech, P., Berggren, Å., Lindberg, J.E., Chhay, T., Khieu, B., Jansson, A., 2016. Growth and survival of reared Cambodian field crickets (Teleogryllus testaceus) fed weeds, agricultural and food industry by-products. Journal of Insects as Food and Feed 2, 285–292.

MINTEL, 2017. Meat-free Foods - UK - May 2017.

MINTEL, 2014. Meat-Free and Free-From Foods-UK. London.

Montoya, M., Reis, A.L., Dixon, L.K., 2018. African swine fever : A re-emerging viral disease threatening the global pig industry. The Veterinary Journal 233, 41–48. doi:10.1016/j.tvjl.2017.12.025

Moritz, M.S.M., Verbruggen, S.E.L., Post, M.J., 2015. Alternatives for large-scale production of cultured beef: A review. Journal of Integrative Agriculture 14, 208–216. doi:10.1016/S2095-3119(14)60889-3

Othman, N., Mohamad, M., Latip, R.A., Ariffin, M.H., 2018. Urban farming activity towards sustainable wellbeing of urban dwellers. Earth and Environmental Science 117. doi:10.1088/1755-1315/117/1/012007

Pellegrino, E., Bedini, S., Nuti, M., Ercoli, L., 2018. Impact of genetically engineered maize on agronomic, environmental and toxicological traits: A meta-analysis of 21 years of field data. Scientific Reports 8, 1–12. doi:10.1038/s41598-018-21284-2

Petersen, B., Niemann, H., Thomas, C., Fuchs, W., 2018. Efficient inhibition of African swine fever virus replication by CRISPR / Cas9 targeting of the viral p30 gene (CP204L) 1–7. doi:10.1038/s41598-018-19626-1

Phalan, B., Green, R., Balmford, A., 2014. Closing yield gaps: perils and possibilities for biodiversity conservation. Phil Trans R Soc B 369, 20120285.

Phalan, B., Green, R.E., Dicks, L. V., Dotta, G., Feniuk, C., Lamb, A., Strassburg, B.B.N., Williams, D.R., Ermgassen, E.K.H.J. zu, Balmford, A., 2016. How can higher-yield farming help to spare nature? Science 351, 450–451. doi:10.1126/science.aad0055

Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. Science 333, 1289–1291. doi:10.1126/science.1208742

Plazzotta, S., Manzocco, L., Nicoli, M.C., 2017. Fruit and vegetable waste management and the challenge of fresh-cut salad. Trends in Food Science & Technology 63, 51–59. doi:https://doi.org/10.1016/j.tifs.2017.02.013

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K., van Vuuren, D.P., 2017. Land-use futures in the shared socio-economic pathways. Global Environmental Change 42, 331–345. doi:http://dx.doi.org/10.1016/j.gloenvcha.2016.10.002

Premalatha, M., Abbasi, Tasneem, Abbasi, Tabassum, Abbasi, S.A., 2011. Energy-efficient food production to reduce global warming and ecodegradation: The use of edible insects. Renewable and Sustainable Energy Reviews 15, 4357–4360. doi:10.1016/j.rser.2011.07.115

Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover : Croplands historical have converted areas. Global Biogeochemical Cycles 13, 997–1027. doi:10.1029/1999GB900046

Ray, D.K., Foley, J.A., 2013. Increasing global crop harvest frequency: recent trends and future directions. Environmental Research Letters 8, 044041. doi:10.1088/1748-9326/8/4/044041

Reuter, H., Middelhoff, U., Graef, F., Verhoeven, R., Batz, T., Weis, M., Schmidt, G., Schröder, W., Breckling, B., 2010. Information system for monitoring environmental impacts of genetically modified organisms. Environmental Science and Pollution Research 17, 1479–1490. doi:10.1007/s11356-010-0334-y

Rickards, L., Howden, S.M., 2012. Transformational adaptation: agriculture and climate change. Crop and Pasture Science 63, 240. doi:10.1071/CP11172

Ricroch, A., Clairand, P., Harwood, W., 2017. Use of CRISPR systems in plant genome editing: toward new opportunities in agriculture. Emerging Topics in Life Sciences 1, 169–182. doi:10.1042/etls20170085

Röös, E., Bajželj, B., Smith, P., Patel, M., Little, D., Garnett, T., 2017. Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. Global Environmental Change 47, 1–12. doi:10.1016/j.gloenvcha.2017.09.001

Röös, E., Patel, M., Spångberg, J., Carlsson, G., Rydhmer, L., 2016. Limiting livestock production to pasture and by-products in a search for sustainable diets. Food Policy 58, 1–13. doi:10.1016/j.foodpol.2015.10.008

Salemdeeb, R., zu Ermgassen, E.K.H.J., Kim, M.H., Balmford, A., Al-Tabbaa, A., 2017. Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. Journal of Cleaner Production 140, 871–880. doi:https://doi.org/10.1016/j.jclepro.2016.05.049

Sánchez-Muros, M.-J., Barroso, F.G., Manzano-Agugliaro, F., 2014. Insect meal as renewable source of food for animal feeding: a review. Journal of Cleaner Production 65, 16–27. doi:https://doi.org/10.1016/j.jclepro.2013.11.068

Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. Proceedings of the National Academy of Sciences 104, 19703–19708. doi:10.1073/pnas.0701976104

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E., Tubiello, F., Smith P.M. Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O.M., C. Mbow, N.H. Ravindranath, C.W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F.T., 2014. Agriculture, Forestry and Other Land Use (AFOLU), in: [Edenhofer, O., R., Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J., Savolainen, S. Schlömer, C. von Stechow, T.Z. and J.C.M. (Eds.), Climate Change 2014: Mitigation of

Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and NY, USA, pp. 811–922.

Specht, K., Siebert, R., Hartmann, I., Freisinger, U.B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., Dierich, A., 2014. Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agriculture and Human Values 31, 33–51. doi:10.1007/s10460-013-9448-4

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., De Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature. doi:10.1038/s41586-018-0594-0

Steinfeld, H., Gerber, P., Wassenaar, T.D., Castel, V., Rosales, M., Rosales, M., de Haan, C., 2006. Livestock's long shadow: environmental issues and options. Food & Agriculture Org.

Steinfield, H., 2006. Livestock's Long Shadow.

Stern, N., Peters, S., Bakhshi, V., Bowen, A., Cameron, C., Catovsky, S., Crane, D., Cruickshank, S., Dietz, S., Edmonson, N., 2006. Stern Review: The economics of climate change. HM treasury London.

Stoate, C., Báldi, A., Beja, P., Boatman, N.D., Herzon, I., van Doorn, A., de Snoo, G.R., Rakosy, L., Ramwell, C., 2009. Ecological impacts of early 21st century agricultural change in Europe – A review. Journal of Environmental Management 91, 22–46. doi:10.1016/j.jenvman.2009.07.005

Su, B., Martens, P., Enders-Slegers, M.-J., 2018. A neglected predictor of environmental damage: The ecological paw print and carbon emissions of food consumption by companion dogs and cats in China. Journal of Cleaner Production 194, 1–11. doi:https://doi.org/10.1016/j.jclepro.2018.05.113

Swain, M., Blomqvist, L., McNamara, J., Ripple, W.J., 2018. Reducing the environmental impact of global diets. Science of the Total Environment 610, 1207–1209.

Syed, M., 2015. Black Box Thinking: The Surprising Truth About Success. John Murray.

Tester, M., Langridge, P., 2010. Breeding technologies to increase crop production in a changing world. Science 327, 818–822.

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U.B., Sawicka, M., 2014. Farming in and on urban buildings : Present practice and specific novelties of Zero-Acreage Farming (ZFarming) 30. doi:10.1017/S1742170514000143

Thornton, P.K., 2010. Livestock production: recent trends, future prospects. Philosophical transactions of the Royal Society of London Series B, Biological sciences 365, 2853–2867. doi:10.1098/rstb.2010.0134

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522. doi:10.1038/nature13959

UN, 2017. World Population Prospects: The 2017 Revision, Key Findings and Advance Tables (No. Working Paper No. ESA/P/WP/248). United Nations, Department of Economic and Social Affairs, Population Division.

van Broekhoven, S., Oonincx, D.G. a. B., van Huis, A., van Loon, J.J. a., 2015. Growth performance and feed conversion efficiency of three edible mealworm species (Coleoptera: Tenebrionidae) on diets composed of organic by-products. Journal of Insect Physiology 73, 1–10.

doi:10.1016/j.jinsphys.2014.12.005

Van Eenennaam, A.L., 2017. Genetic modification of food animals. Current Opinion in Biotechnology 44, 27–34. doi:10.1016/j.copbio.2016.10.007

van Huis, A., 2013. Potential of Insects as Food and Feed in Assuring Food Security. Annual Review of Entomology 58, 563–83. doi:10.1146/annurev-ento-120811-153704

van Huis, A., Oonincx, D.G.A.B., 2017. The environmental sustainability of insects as food and feed. A review. Agronomy for Sustainable Development 37, 43. doi:10.1007/s13593-017-0452-8

Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance-A review. Field Crops Research 143, 4–17. doi:10.1016/j.fcr.2012.09.009

Vermeulen, S.J., Dinesh, D., Howden, S.M., Cramer, L., Thornton, P.K., 2018. Transformation in Practice: A Review of Empirical Cases of Transformational Adaptation in Agriculture Under Climate Change. Frontiers in Sustainable Food Systems 2. doi:10.3389/fsufs.2018.00065

Wellesley, L., Happer, C., Froggatt, A., 2015. Changing climate, changing diets: pathways to lower meat consumption. Royal Institute of International Affairs, Chatham House.

West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K. a., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328. doi:10.1126/science.1246067

West, P.C., Gibbs, H.K., Monfreda, C., Wagner, J., Barford, C.C., Carpenter, S.R., Foley, J.A., 2010. Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. Proceedings of the National Academy of Sciences 107, 19645–19648. doi:10.1073/pnas.1011078107

White, M., 2017. Vast vertical farms growing much, much more with less [WWW Document]. AgInnovators. URL https://www.aginnovators.org.au/news/vast-vertical-farms-growing-far-far-more-less (accessed 9.17.18).

Wielemaker, R., Oenema, O., Zeeman, G., Weijma, J., 2019. Science of the Total Environment Fertile cities : Nutrient management practices in urban agriculture. Science of the Total Environment 668, 1277–1288. doi:10.1016/j.scitotenv.2019.02.424

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., Declerck, F., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Reddy, K.S., Narain, S., Nishtar, S., Murray, C.J.L., 2019. The Lancet Commissions Food in the Anthropocene : the EAT – Lancet Commission on healthy diets from sustainable food systems. Lancet. doi:10.1016/S0140-6736(18)31788-4

Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems 103, 621–638. doi:10.1016/j.agsy.2010.07.005

Zorya, S., Morgan, N., Diaz Rios, L., Hodges, R., Bennett, B., Stathers, T., Mwebaze, P., Lamb, J., 2011. Missing food: the case of postharvest grain losses in sub-Saharan Africa.

zu Ermgassen, E.K.H.J., Phalan, B., Green, R.E., Balmford, A., 2016. Reducing the land use of EU pork production: where there's swill, there's a way. Food Policy 58, 35–48. doi:https://doi.org/10.1016/j.foodpol.2015.11.001